High-Resolution Simulations of Clusters of Galaxies

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Cosmology with Clusters of Galaxies

- **Clusters of galaxies are potentially very powerful cosmological probes, complementary to the SNIa and CMB anisotropies**

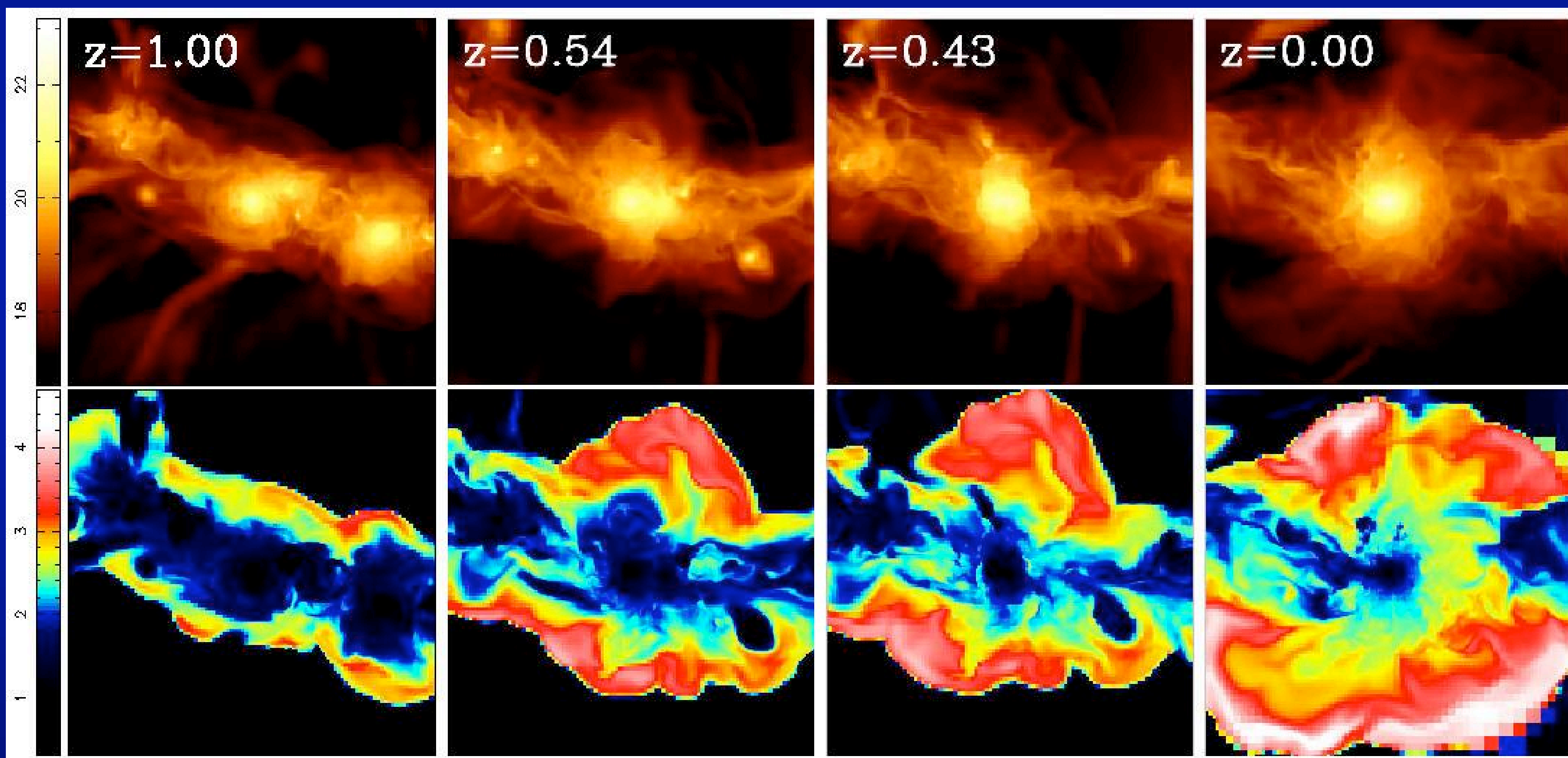
  The abundance of clusters above a certain mass in a given area of the sky as a function of redshift is very sensitive to the amplitude and growth rate of perturbations, as well as the comoving volume per unit redshift and solid angle. These, in turn, are sensitive to the energy density of matter Ω_m and the energy density Ω_{DE} and, ultimately, the equation of state w parameter of the dark energy. Many upcoming surveys will be able to detect hundreds of clusters over a wide range of redshifts, particularly over the epoch of dark energy domination (z<1). Measurements of the abundance of clusters as a function of redshift produced by these cluster surveys can place tight constraints on cosmological parameters.

- **Understanding detail cluster gas structure & its evolution is critica**

  In order to realize the full statistical power of the upcoming cluster surveys, we mus understand the relation between observable properties of clusters and their mass. This is because the most accurate theoretical predictions for cluster abundance are as a function of cluster mass, which is not a direct observable. Therefore, the evolution of the intracluster gas and the role of physical processes such as gas cooling, star formation, stellar feedback, and thermal conduction, which affect its observable properties, must be studies using both numerical simulations and observations.

N-body + Gasdynamics Cluster Simulations

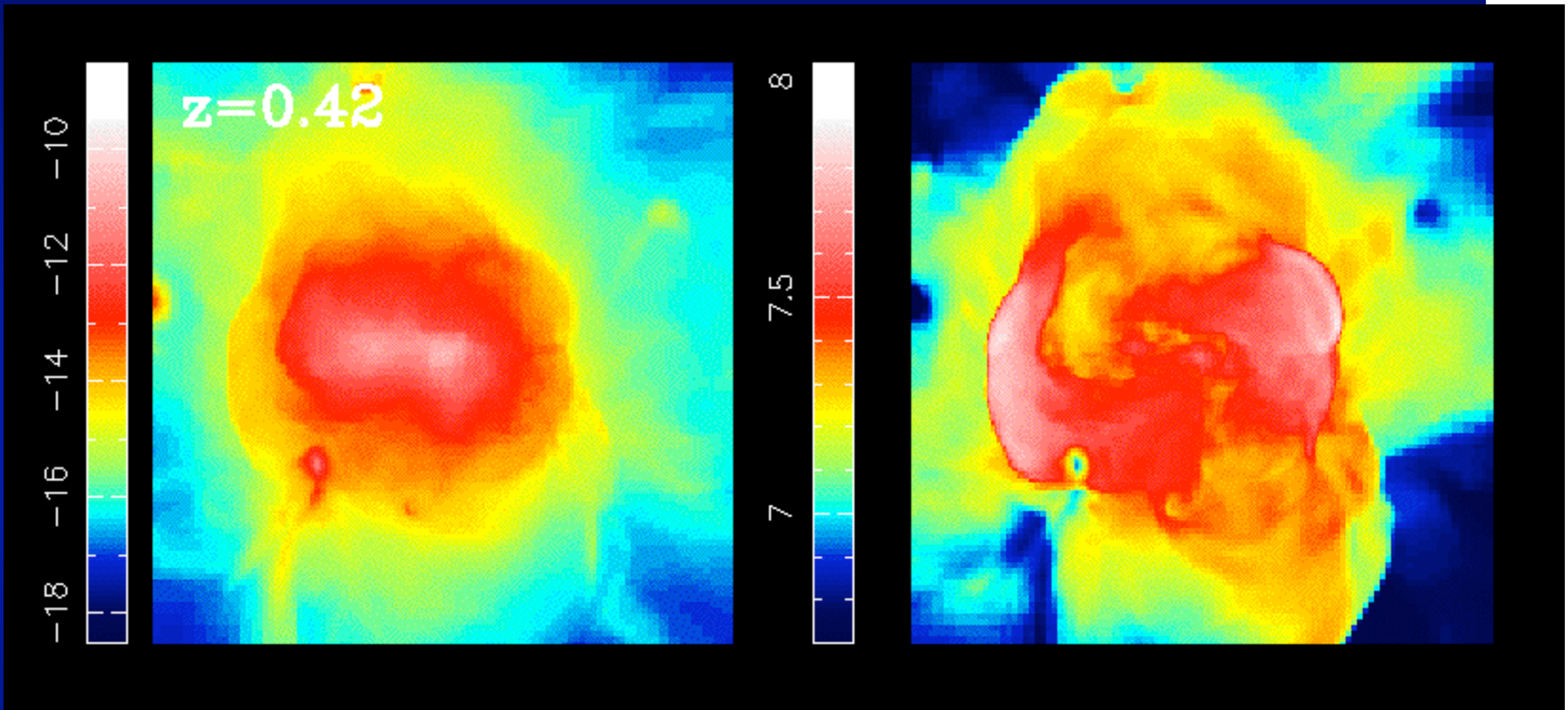
We are carrying out a series of very high-resolution simulations of cluster formation using the A code [Kravtsov et al. 2002, ApJ571, 563]. The code achieves high spatial resolution (~5h^{-1} kpc) the central regions of clusters using Adaptive Mesh Refinement (AMR) algorithm and uses eule gas dynamics with good shock-capturing characteristics. The simulations are being used for detailed comparions with observations. Here we present several examples of such comparions.



The maps of projected gas density (top) and entropy (bottom) of a simulated □CDM cluster color-coded on $\log_{10}$ scale in units of cm^2 (density) and keV cm^2 (entropy). The size of the region shown is 8h^{-1} Mpc. T entropy maps reveal a very complex entropy distribution of the gas. Both the filaments and the forming clust are surrounded by strong and aspherical accretion shocks. At z=0 the low-entropy filamentary gas trailing t

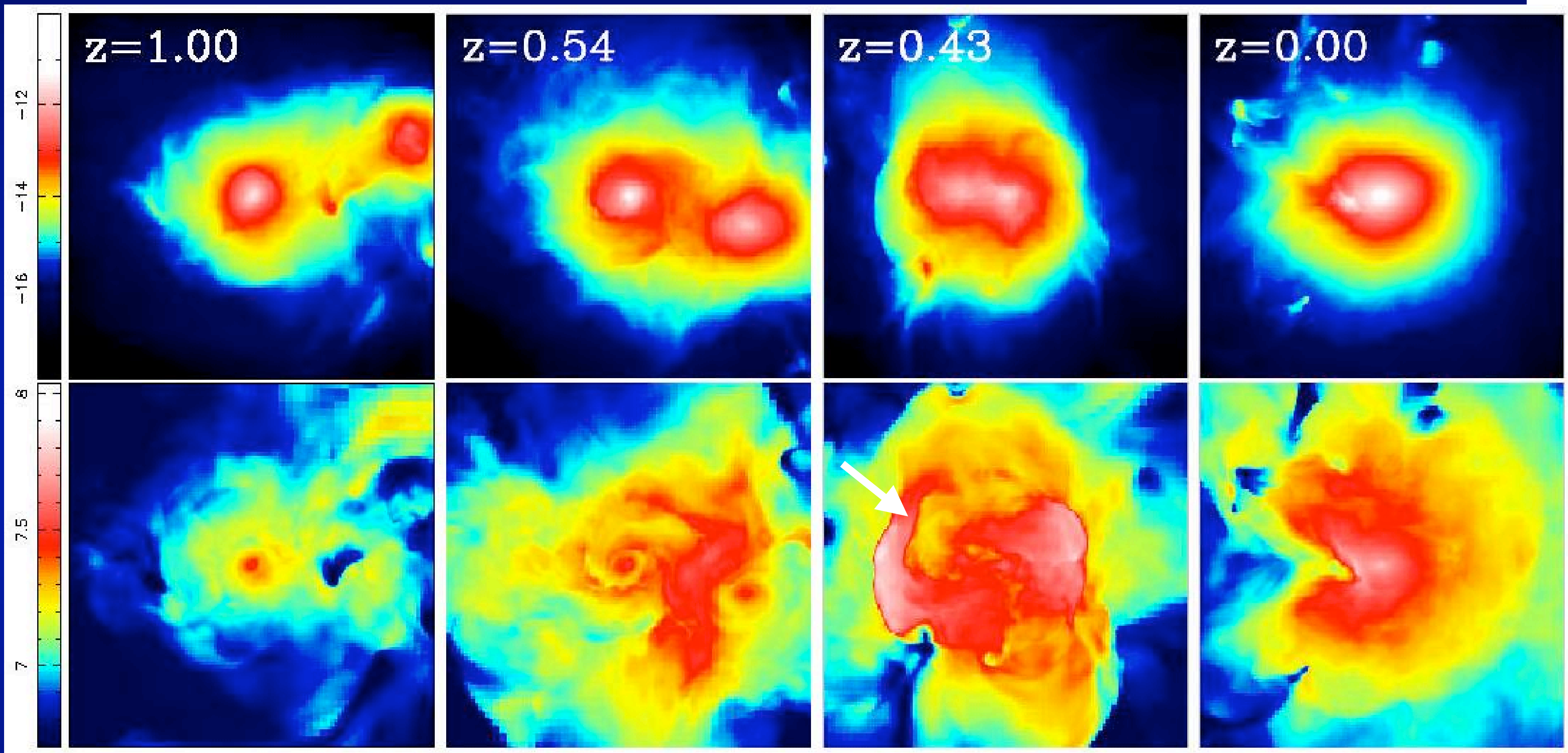
[Nagai & Kravtsov, 2002,astro-ph/0206469]

X-ray surface brightness and temperature



The X-ray surface brightness (top) and emission weighted temperature (bottom) of the simulated CD cluster. The maps are color-coded on a $\log_{10}$ scale in units of erg s^{-1} cm^{-2} $arcmin^{-2}$ (surface brightness) a keV (temperature) in the 0.5-2 keV band. The size of the volume shown is $2h^{-1}$ Mpc. Note that cold, dense (the cold front) associated with the merging sub-cluster appears in the tail of the merger shock front (z=0 panel, the front is indicated by arrow). The merging subclump is trailed by a relatively cold (~1-2 ke intergalactic gas accreted along a filament. [Nagai & Kravtsov, 2002, astro-ph/0206469]

X-ray surface brightness and temperature



The X-ray surface brightness (top) and emission weighted temperature (bottom) of the simulated □CD
cluster. The maps are color-coded on a $\log_{10}$ scale in units of erg s^{-1} cm^{-2} $arcmin^{-2}$ (surface brightness) a
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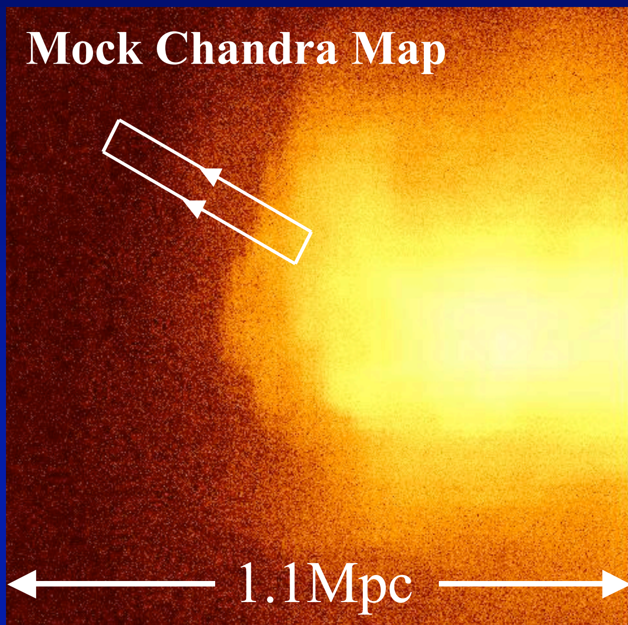
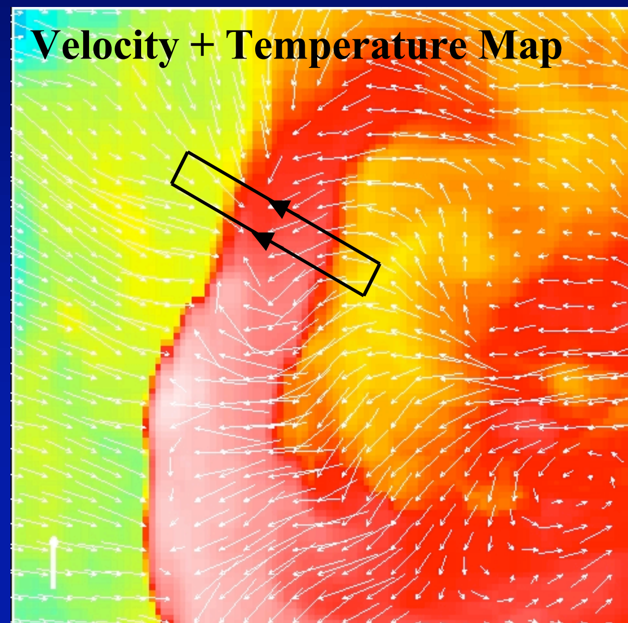
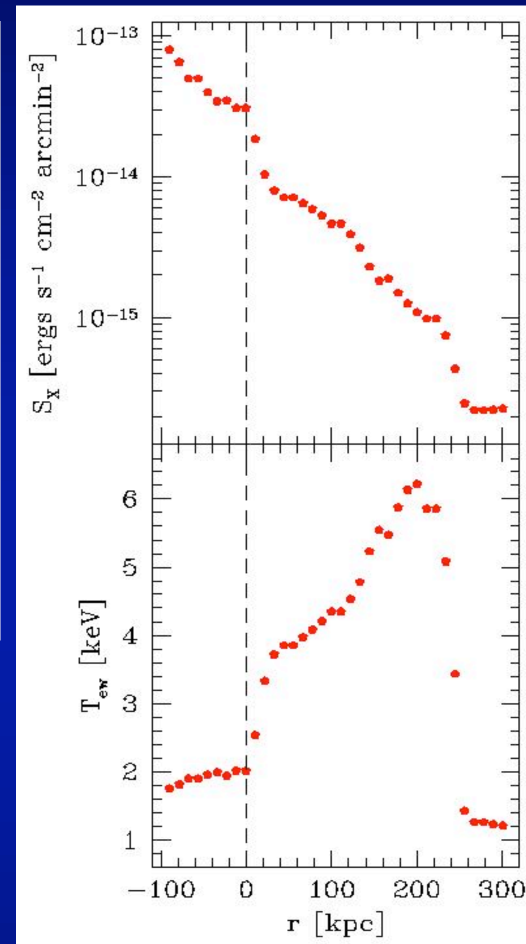
Shock & Cold Fronts in CDM clusters







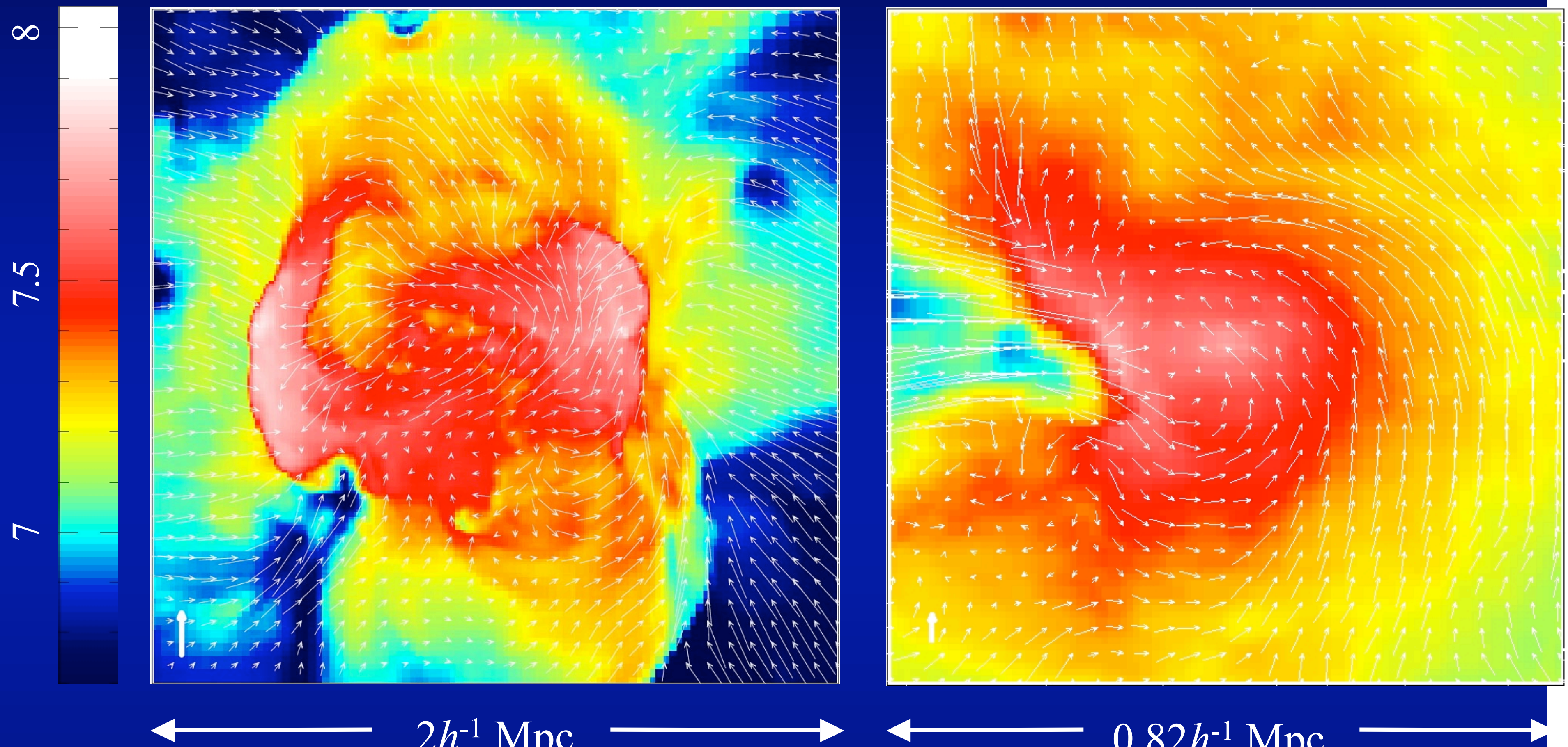
Left panel : The mock Chandra X-ray map of shock and cold fronts identified in the z=0.43 panel.

Middle panel : The velocity map overlaid on temperature map of the same region. The length of the thick vertical vector in the bottom-left corner corresponds to 1000 km s^{-1}.

Right panel : The X-ray surface brightness (top) and emission weighted temperature (bottom) profiles in the rectangular boxes shown. Across the cold front (shown by dashed line), a jump in surface brightness is accompanied by a drop in temperature over the scale of ∼30 kpc, comparable to the observations. The profiles also show the presence of a blow shock ∼ 200 kpc from the cold front. The region around ths shock, however, has a very low X-ray brightness. The velocity field shown in the middle panel shows that the cold front is a non-equilibrium phenomena arising during cluster mergers

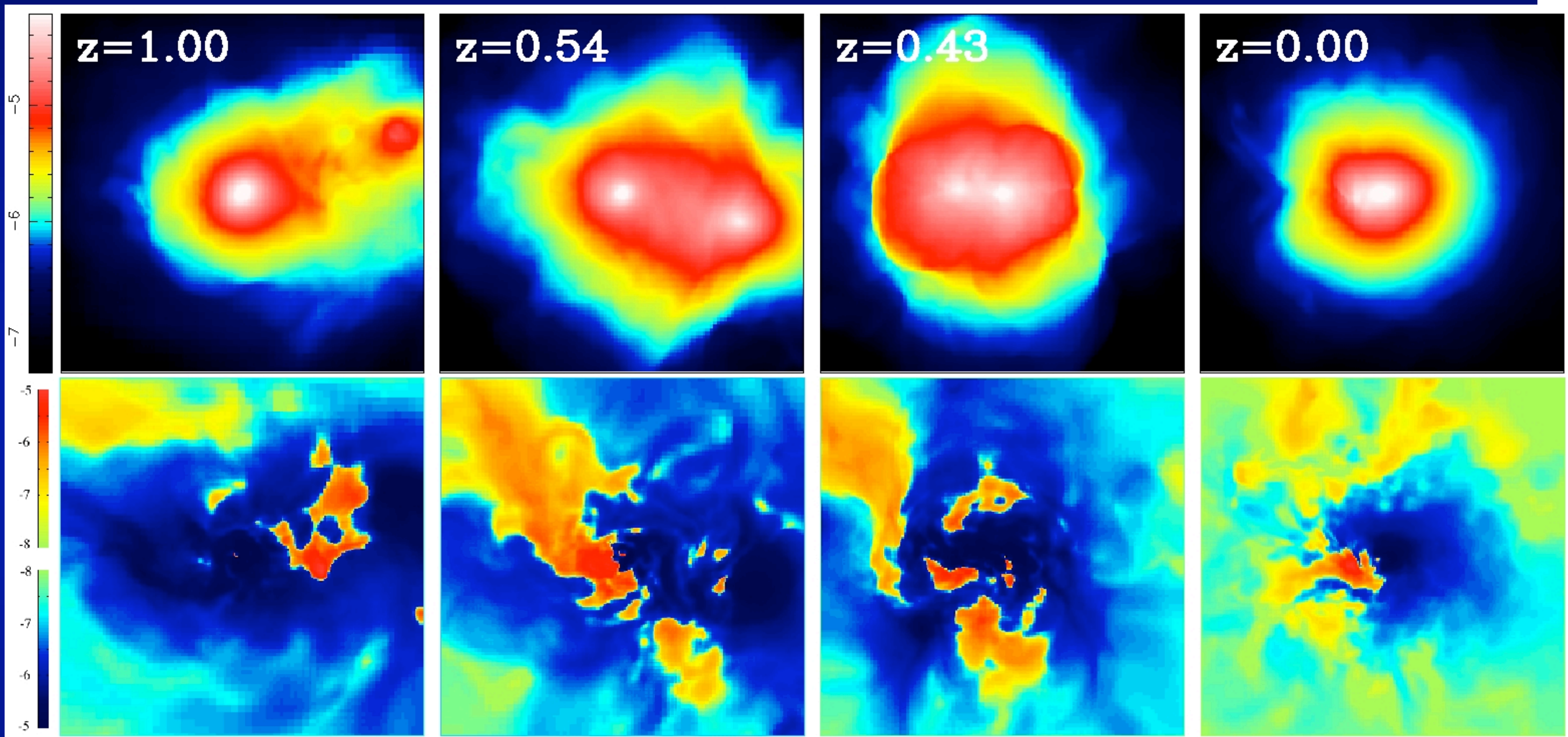
[Nagai & Kravtsov, 2002]

Internal motions of gas in clusters



Internal gas flows during a major merger (z=0.43, left) and when the cluster is in a relatively relaxed state (z=0, right). The velocity field is overlaid on the color maps of the emission-weighted temperature, color-coded on a $\log_{10}$ scale in units of Kelvin. The vertical vectors in lower left corner correspond to 1000 km/s and 500 km/s in the left and right panels, respectively. The maps show that major mergers are accompanied by violent flows of gas. The gas is moving with velocities of 200-500 km/s even in the cores of relaxed clusters [Nagai, Kravtsov & Kosowsky 2002, astro-ph/0208308]

Thermal & kinetic SZ effect



The thermal (top) and kinetic SZ (bottom) effect of the simulated ΛCDM cluster. The maps are color-coo on a $\log_{10}$ scale in dimensionless units. The size of the volume shown is $2h^{-1}$ Mpc. The thermal SZ maps sh smooth gas pressure distribution, except when clusters are experiencing major merger. Note that the sh pressure discontinuity associated with the merger shock fronts are shown in both directions of the merger a in the z=0.43 panel. The kinetic SZ maps show a complex spatial structure of kSZ distortion signal associa with internal motion of cluster gas and merging subclumps. [Nagai, Kravtsov & Kosowsky, 2002]